2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #50227

The Efficacy of Project Integration in Undergraduate Heat Transfer Education

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Quantifying Conceptual Mastery in Heat Transfer: A Mixed-Methods Evaluation of Project-Based Learning

Abstract

Heat transfer is critical for real-world applications including HVAC systems, automotive cooling, power generation, industrial processes like drying and chemical reactions, and the design of insulation and renewable energy systems, all of which rely on managing heat flow. While Project-Based Learning (PBL) is recognized for its ability to bridge the gap between theory and practice, empirical evidence mapping the transition from mathematical computation to qualitative visualization in thermal engineering remains limited. This study evaluates the effectiveness of diverse thermal engineering tasks—ranging from Baja car gearboxes to double-glazed windows—using a mixed-methods assessment framework conducted with a junior-level Heat Transfer cohort (N=18). Quantitative learning gains were calculated using the normalized Hake factor (g), while qualitative cognitive depth was analyzed via student reflections coded against the SOLO (Structure of Observed Learning Outcomes) taxonomy. Data from nine distinct projects revealed varying levels of mastery, with 44% of groups achieving high mastery ($g > 0.70$) and reaching 'Deep' levels of critical analysis. Conversely, one project resulted in low growth ($g < 0.30$), identifying a need to restructure descriptive tasks into optimization-based challenges. The results demonstrate that correlating raw knowledge acquisition with thematic reflection analysis provides a robust measure of a student's ability to apply critical thinking to complex engineering systems. This dual-assessment model offers engineering practitioners a standardized tool for evaluating conceptual shifts in abstract thermal sciences.

1. Introduction

While the efficacy of Project-Based Learning (PBL) has been documented across various educational levels—ranging from systematic reviews in primary education [1] to specialized aerospace laboratory applications [2] a significant gap remains in thermal engineering pedagogy. Specifically, there is limited empirical evidence exploring how PBL facilitates the mastery of abstract, multi-dimensional concepts such as thermal boundary layer visualization, which students frequently struggle to move beyond mathematical computation. Furthermore, existing literature often prioritizes final project outcomes over the underlying cognitive progression of the learner. This study addresses these deficiencies by employing a mixed-methods framework to correlate quantitative learning gains with the qualitative shift from surface-level descriptions to deep, critical analysis in heat transfer applications. Every PBL experience initiates with an introduction to a set of user-defined performance requirements. It is essential to formulate a clear and concise design objective statement, which serves as the foundation for deriving functional requirements (what the design must accomplish) and identifying potential conceptual solutions (how those requirements will be met) [3,4,5]. Project-Based Learning (PBL) establishes a contextual environment that renders education both engaging and professionally relevant. By offering students the opportunity to explore technical challenges from a system-level perspective, PBL fosters a profound appreciation for the inherent interconnectedness of science and engineering [6]. Novia Ananda Putri et al. investigated the impact of an 8E learning cycle model, supported by flipbook e-modules, on improving high school students' mastery of heat and thermodynamics concepts [7]. On the other hand, when students utilize modern software such as SolidWorks, ANSYS, and Engineering Equation Solver (EES) [8], they develop a deeper understanding of complex engineering systems. In the domain of physics and engineering education, standardized research-based conceptual instruments have emerged as the gold standard for evaluating instructional efficacy [9]. Validated tools, such as the Force Concept Inventory (FCI) [10] and the Force and Motion Conceptual Evaluation (FMCE) [11], have established the utility of measuring conceptual shifts in Newtonian mechanics. Following the conventions of Physics Education Research (PER), this study adopts a pretest-posttest experimental design to quantify the delta between student's entry-level preparation and their end-of-term proficiency [12–14]. By implementing this dual-assessment model, we can isolate the 'learning gain' attributable to Project-Based Learning (PBL) interventions, providing a standardized metric to evaluate the transition from rote memorization to conceptual mastery.

The study involved N=18 undergraduate mechanical and electromechanical students (9 teams of two) enrolled in a Junior-level Heat Transfer course at Wentworth Institute of Technology. The objective of this project is to employ a mixed-methods assessment framework. Quantitative growth was evaluated using Absolute and Normalized Gains derived from pre- and post-project scores, while qualitative depth was analyzed by categorizing student reflections into Surface, Emerging, and Deep learning levels.

2- Methodology

2.1 Study Context and Participants

This study was conducted during the [Summer/2025] semester in a required Heat Transfer course. The participant pool consisted of 18 mechanical and electro-mechanical engineering students.

2.2 Mixed-Methods Design

A convergent parallel mixed-methods design was employed:

- **Quantitative:** The quantitative data was collected via a 15-item Comprehensive Heat Transfer Assessment (CHTA) administered both at the onset of the project (pre-test) and upon completion (post-test). Pre- and post-tests consisting of 3 conceptual and 5 calculation-based questions were administered. Learning gain was calculated using the Hake factor [15]:

$$g = (\%post - \%pre)/ (\%100 - \%pre)$$

- **Qualitative:** The qualitative assessment focused on the cognitive depth and metacognitive growth demonstrated in student reflections. The rubric (Table 2) was adapted from the SOLO Taxonomy [16], categorizing responses based on how students connected individual concepts to a system-level understanding. Qualitative data were gathered through student reflections, which were assessed to identify Surface, Emerging, and Deep learning levels according to the criteria established in Table 2

3. Projects

Teams of two students worked on heat transfer projects of their choice. One such project involved the design and thermal management of a Baja Car Gearbox for the Wentworth SAE Baja team. In this case, the heat transfer rate was determined based on historical data and environmental conditions. This rate was then compared to the expected heat generation to ensure the new design would not overheat during operation. Such evaluations are critical to the design process, allowing for the identification of potential failures before incurring construction expenses. Table 1 lists the various projects, with each project identified by a corresponding number. For example, figure 1 illustrates the assembly for Project #2, featuring the engine and the shielded chain-and-sprocket system previously utilized for torque conversion. This configuration experienced catastrophic thermal failure during operation; the lack of ventilation caused overheating that damaged the clutch and led to total mechanical failure. To mitigate these risks in the current vehicle, a custom gearbox was engineered with an emphasis on thermal management. The objective is to evaluate the design's heat transfer capabilities to ensure adequate dissipation of frictional heat during a four-hour endurance race. As shown in Figure 2, the gearbox housing consists of two machined 6061 aluminum shells integrated with cooling fins to maximize convective surface area. For safety and operational reasons, one shell face remains exposed to ambient air, while the other is shielded. The assembly will be lubricated with 75W-90 gear oil and equipped with a pressure relief valve (not modeled) to manage internal pressure during thermal expansion.

Figure 1. 2024-2025 Wentworth Baja Car Rear End

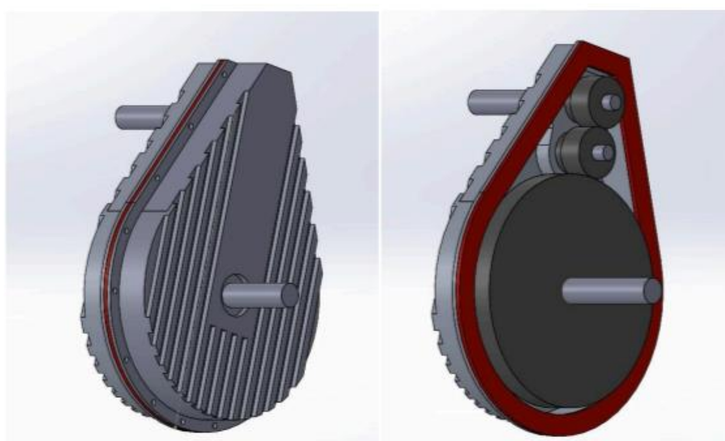

Figure 2. Gearbox Assembly (Left), Internal View of Gears & Inner Shell (Right)

Table 1. list of various projects

Project #	List of the Projects
1	Car Radiator
2	Design and build Baja Car Gearbox Thermal Management
3	Thermoplastic Composite Pipe
4	Steam Condenser Analysis
5	Heat Sink
6	Heat exchanger
7	Heat Transfer Through a Boiler Wall
8	Heat Transfer in Gun Barrels
9	Thermal Behavior of Double-Glazed Windows

4. Assessment Tools:

4.1 Quantitative Analysis: Measuring Growth

Using pre- and post-project scores is a standard way to calculate Learning Gain, as illustrated in Figure 3. Absolute Gain evaluates the "new points" a student earned during the project (the simple difference between scores). However, Normalized Gain (g) is often more insightful because it measures growth relative to the student's potential for improvement. As shown in Figure 4, this allows for a fairer comparison between students starting at different levels.

For example, Figure 4 shows that while the "Thermoplastic Composite Pipe" group achieved high normalized gains, the "Steam Condenser Analysis" group showed lower gains and remained at a "Surface" level in their qualitative reflections. This suggests that the steam condenser project may have been too descriptive and would benefit from more open-ended problem-solving elements next year. Additionally, it was observed that three students moved from the "Fail" category in the pre-test to the "Mastery" category in the post-test.

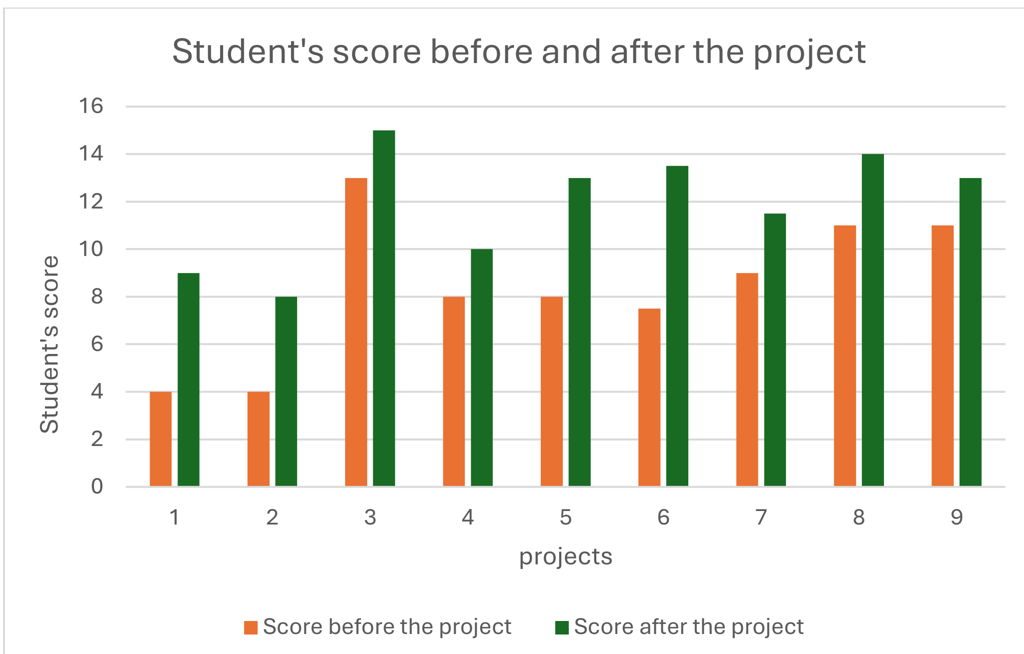

Figure 3. Student’s score before and after the project

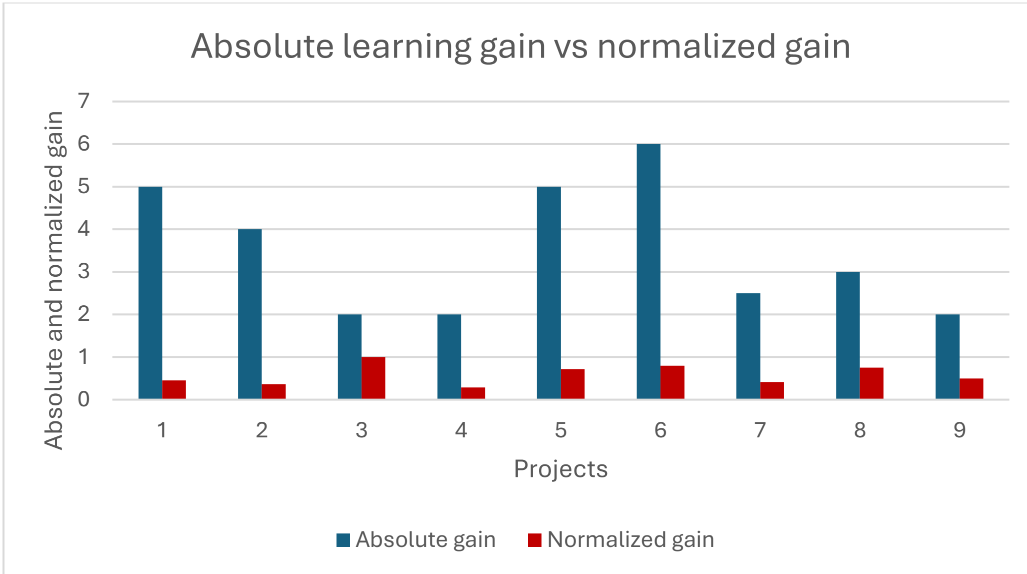

Figure 4. Absolute gain vs. normalized gain

4.2 Qualitative assessment focuses on the quality, depth, and process of learning rather than just the final score. In the project, using student reflections is the perfect way to capture this. Students were able to recognize their own learning processes and describe the challenges they faced and how they overcame them. Additionally, their confidence in the subject matter increased, and they demonstrated effective teamwork skills.

Table 2. Qualitative Assessment Rubric: Project Reflections

List of Projects	**Surface (Descriptive only)**	**Emerging (Connects to theory)**	**Deep (Critical thinking)**	**Heat transfer mode**
Car Radiator	Describes the radiator as a series of tubes and fins used to cool the engine coolant using air.	Explains the Heat Transfer Coefficient (h) and how the finned surface area increases the rate of convection.	Analyzes the impact of "fouling" (dirt/debris) on thermal performance over time.	Conduction And Convection

List of Projects	Surface (Descriptive only)	Emerging (Connects to theory)	Deep (Critical thinking)	Heat transfer mode
Baja Car Gearbox Thermal Management	Described the parts of the gearbox and noted that it gets hot during operation.	Connected heat generation to friction and fluid viscosity theories.	Evaluated different cooling fins or lubricants to optimize heat dissipation under racing conditions.	Conduction and Convection
Thermoplastic Composite Pipe	Listed the materials used and the physical dimensions of the pipe.	Explained how thermal conductivity differs between polymer layers and reinforcements.	Analyzed the impact of thermal expansion on structural integrity and predicted failure points.	Conduction, convection, and Radiation
Steam Condenser Analysis	Described the condenser setup and recorded inlet/outlet temperatures.	Applied the First Law of Thermodynamics to calculate the rate of heat condensation.	Optimized the mass flow rate to improve efficiency and discussed the impact of non-condensable gases.	Conduction, and convection,
Heat Sink	Mentioned that the heat sink was attached to a component to keep it cool.	Used Newton's Law of Cooling to explain how surface area affects heat transfer.	Critiqued the fin geometry and material choice (e.g., Al vs. Cu) based on weight-to-performance ratios.	Conduction, And convection,

List of Projects	Surface (Descriptive only)	Emerging (Connects to theory)	Deep (Critical thinking)	Heat transfer mode
Heat Exchanger	Described the flow of hot and cold fluids through the tubes.	Calculated the Log Mean Temperature Difference (LMTD) to determine heat transfer effectiveness.	Designed a counter-flow modification to maximize energy recovery and justified the cost-benefit.	Conduction, and convection,
Heat Transfer Through a Boiler Wall	Noted the thickness of the wall and the fuel being burned inside.	Calculated the conductive heat flux through multiple layers of insulation and steel.	Investigated the effects of scaling or "fouling" on the wall and proposed a maintenance schedule to save fuel.	Conduction, and convection,
Heat Transfer in Gun Barrels	Described the rapid heating of the barrel after multiple shots.	Modeled the transient heat conduction and the convection cooling from the surrounding air.	Analyzed the thermal stresses that cause barrel warping and suggested material coatings to extend barrel life.	Conduction And Convection
Thermal Behavior of Double-Glazed Windows	Mentioned that the window has two glass panes with a gap in between.	Explained how the air/argon gap reduces heat loss through conduction and convection.	Evaluated the "U-value" in different climates and performed a cost-saving analysis for a building's HVAC load.	Conduction, Convection And radiation

5. Results

This study was conducted during the [summer/2025] semester in a required Heat Transfer course. The participant pool consisted of 18 mechanical engineering students.

5.1 Quantitative Results: Learning Gains

Table 2 presents the qualitative assessment rubric for project reflections. In educational research, a normalized gain (g) above 0.70 is generally considered a high gain. The following analysis is derived from the data in Table 2:

- Project 3 (g = 1.0 / 100%): This is a perfect result. Even though the absolute gain was small (2 points), the student mastered 100% of the material they didn't know. This suggests the project was perfectly targeted for their level.
- Project 6 (g = 0.8 / 80%) and Project 8 (g = 0.75 / 75%): These are very strong results. These students showed both high raw improvement (6 and 3 points) and high efficiency in learning.
- Project 4 (g = 0.28 /28.5%): This is the lowest performer. They only gained 2 absolute points and achieved less than a third of their potential growth. This is due to that the students find the instructions confusing or they have a teamwork issue. The data suggests they struggled to grasp the core concepts compared to the others.

Compare Project 1 and Project 5.

- Both have an Absolute Gain of 5.
- However, Project 5 has a much higher Normalized Gain (71.4%) compared to Project 1 (45.4%).
- Analysis: This shows that the student in Project 5 started with a much higher pre-score and mastered almost all remaining content. The student in Project 1 improved by the same number of points but still has a lot of "room to grow."

Table 3 summarizes the results into categories to show the overall effectiveness of the teaching method.

Table 3. Summary of the overall effectiveness of teaching method:

Performance	Project Numbers	Interpretation
High Mastery (g > 0.7)	3, 5, 6 and 8	These projects were highly effective. Students achieved near-total mastery of the subject.
Moderate growth (0.3 > g > 0.7)	1, 2, 7, and 9	Students learned well, but there is still significant room for additional instruction.
Low growth (g<0.3)	4	The project or student faced significant barriers to learning.

5.2 Qualitative Results: Depth of Mastery

To validate the quantitative gains, student reflections were analyzed using the SOLO Taxonomy (see Table 2). Table 4 presents a correlation between the quantitative learning gains and the qualitative levels of mastery for each project. The qualitative findings reinforce the quantitative data:

- Alignment of High Gains and Deep Thinking: Students in high-gain projects (e.g., Project 3: Thermoplastic Composite Pipe) consistently demonstrated 'Deep' learning. Their reflections moved beyond describing the pipe's materials to analyzing how thermal expansion would impact structural integrity and predicting failure points under stress.
- Surface Learning in Low-Gain Projects: The 'Low Growth' observed in Project 4 (Steam Condenser) was mirrored in the qualitative data. These students remained at the 'Surface' level, documenting inlet/outlet temperatures and setup dimensions without connecting these observations to the underlying phase-change thermodynamics.

Table 4. Correlation of Quantitative Gains and Qualitative Learning Levels

Project #	**Normalized Gain (g)**	**Mastery Category**	**Qualitative Level (SOLO)**
3, 5, 6, 8	0.75 – 1.00	High Mastery	Deep
1, 2, 7, 9	0.30 – 0.71	Moderate Growth	Emerging
4	0.28	Low Growth	Surface

5.3 Work in progress:

Projects that yielded 'Low Growth' (Normalized Gain < 0.3) will be restructured from descriptive tasks to optimization-based challenges to force higher-level cognitive engagement. While the current N=18 provides localized insight, future iterations will aggregate data across multiple sections to perform t-test analyses and determine if specific project types (e.g., phase-change vs. steady-state conduction) yield statistically significant differences in learning gains.

Conclusion

The assessment of these projects confirms that a hands-on, project-based approach significantly enhances student understanding of heat transfer and thermal management. Quantitative analysis showed a broad range of improvement, with several projects (specifically Projects 3, 5, 6, and 8) achieving "High Mastery" status with normalized gains exceeding 70%.

Qualitatively, the shift from "Surface" descriptions to "Deep" critical thinking was evident in student reflections; successful students moved beyond simply describing components to optimizing thermal efficiency and analyzing failure modes. The correlation between high normalized gains and deep reflections suggests that when students are challenged to troubleshoot and iterate—as seen in the Baja Car Gearbox and Steam Condenser projects—they achieve a higher level of metacognitive awareness and professional confidence. Future iterations of this curriculum should focus on providing the "Low Gain" projects with more open-ended problem-solving opportunities to push students toward deeper analytical levels. While overall class performance was strong, Project 4 served as a case study for instructional adjustment. By shifting the project from a descriptive task to an optimization-focused challenge, we aim to bring its Normalized Gain in line with the high-performing projects (e.g., Projects 3 and 6) in the next cycle. Projects that yielded 'Low Growth' (Normalized Gain < 0.3) will be restructured from descriptive tasks to optimization-based challenges to force higher-level cognitive engagement.

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